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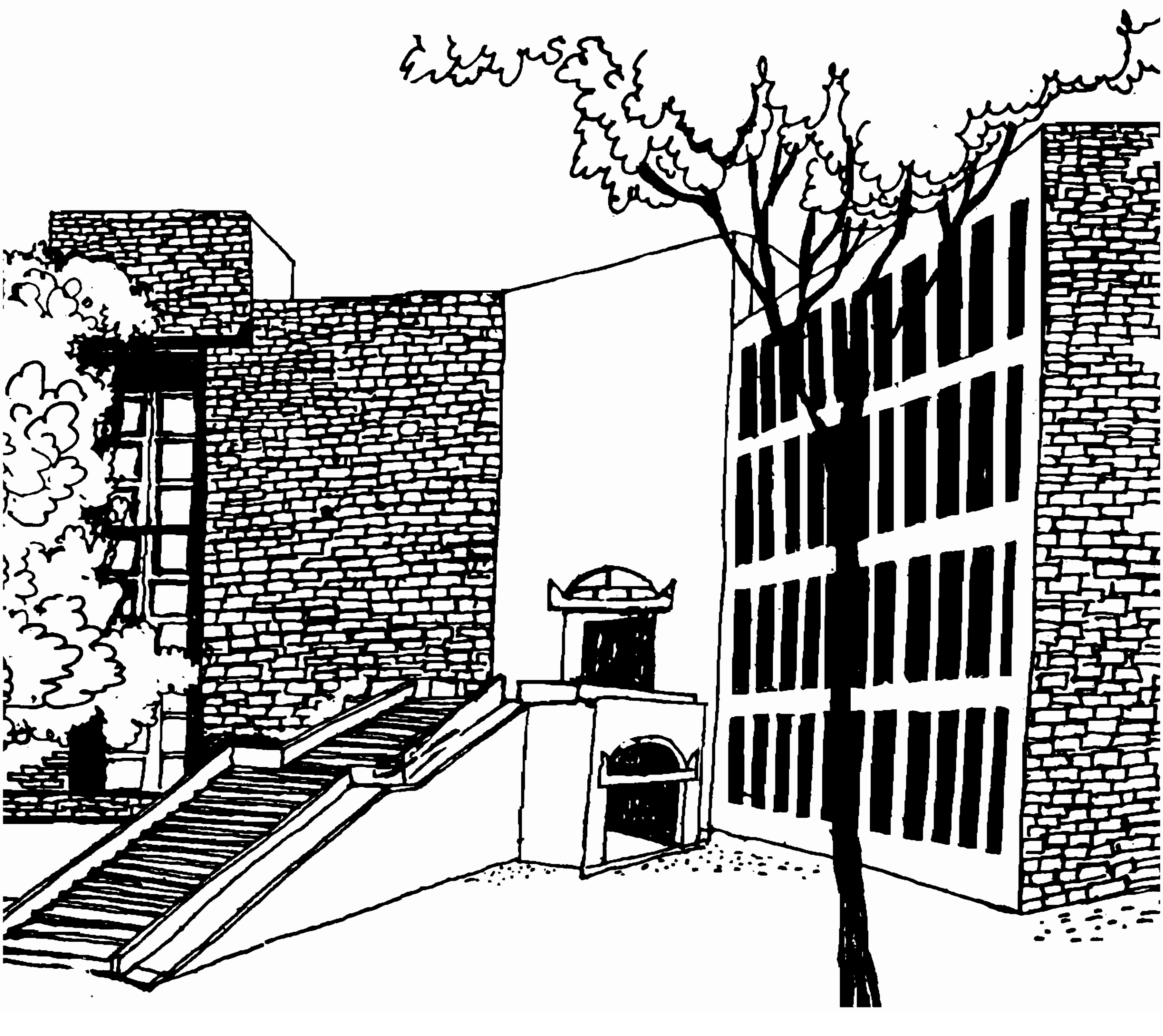

A Multiple Objective Model for Sustainable Micro-Watershed Planning with Application

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Abstract

A watershed is a hydrological unit of space composed of interrelated drainage area with a common movement of water including all the consequential implications for land and water use. A micro-watershed is a coherent ecosystem at the smallest viable geographical area. It is administratively as well as operationally the most meaningful planning unit. Micro-watershed planning contributes to sustainable development of the area by integrating varied development programmes through the efficient use, equitable access and decentralised control of water resources. This paper presents a planning model for micro-watershed development. Three objectives are considered as adequate to represent the sustainable development ethos. These are - economic benefits essentially accruing to land and cattle owners, employment benefits accruing to labouring sections and soil conservation which contributes to long-term sustainability of land.

Project options available to a planner are check dams, gully checks, contour bunds, pond development, pasture development and afforestation. Constraints include investment budget, lower limit on benefit-cost ratio, availability of land for pasture development, afforestation and pond construction. Besides these there are constraints to ensure system relationship logic. The model formulation results in a multiple objective mixed-integer linear formulation wherein objectives and constraints are linear functions of decision variables.

A real-life application of the model is presented. A representative group of community is considered as a decision maker (DM). DM's preferences are modelled as a value function which is encoded through a series of questions and answers. We have termed the value function as "Sustainability Index" as it evaluates in a single measure the efficacy of the plan in terms of sustainable development. The decision problem is to select a development plan that maximises Sustainability Index.

For the present application, the planning problem results in a concave objective function with eighteen linear constraints, twentyfive zero-one and five continuous variables. An algorithm that uses a branch and bound procedure together with an implicit enumeration logic is developed to solve the problem. The algorithm solves a continuous non-linear problem at each node of the branch and bound tree. Compared to a plan developed by a local agency, the optimal plan improves achievement of each objective by twentyfive percent. Sensitivity analysis with varying budget limits is carried out which recommends additional investment beyond the current budget. Improvement of the model through integration of energy and environment options and some features of suitable database to aid the planner are presented.

1.0 Introduction

A watershed is a hydrological unit of space composed of interrelated drainage area with a common movement of water including all the consequential implications for land and water use (Tolley et al. 1961). It is a natural drainage area tied together physically by an interrelated stream and drainage pattern. A watershed system may comprise of millions of hectares to a micro watershed of few hundred hectares. In India, water resources system is classified into 6 water resource regions, 35 basins, 112 catchments, 500 sub-catchments and 3,200 watersheds. A watershed can comprise of several micro-watersheds (Report by Department of Economics, Himachal Pradesh University 1986). Figure 1 gives a map of watershed drained through point x. The watershed comprise of several micro-watersheds systems (e.g. A) drained by their own waterways.

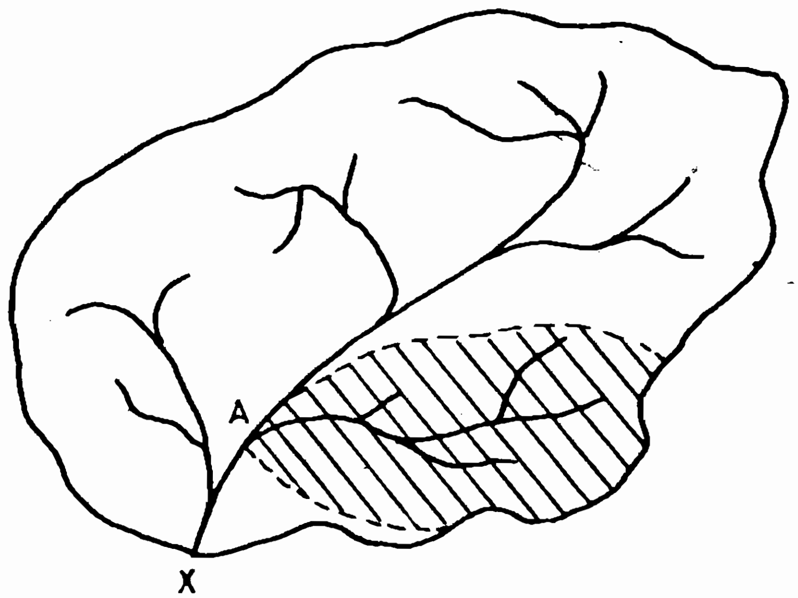
A Micro-watershed is a meaningful and coherent ecosystem at the smallest viable geographical area. It is administratively as well as operationally the most meaningful planning unit for sustainable rural development. It comprises of a few villages with a defined characteristics of habitat, natural resources, socio-cultural life pattern and levels of economic activities.Watershed being a natural hydrological identity responds more effectively to various engineering, biological and agricultural treatments designed to improve land productivity and sustainability. Micro-watershed thus is a meaningful planning unit for integrating varied development programmes such as for agriculture, forestry, fodder, industry, energy and water together with decentralised administration which is an essential prerequisite of successful sustainable development.

In a developing country like India, second only to land, water is the most crucial resource for sustainance of all rural activities. Availability and utilization of water determines the scale and productivity of economic activities such as agriculture, animal husbandary, village crafts (e.g. leather, handloom etc.) besides sanitation and health. Naturally therefore, planning for sustainable rural development should center around management of water resources. While ground water is most significant contributor towards India's achievements in agriculture in last two decades, there has been increasing evidence of over-exploitation of ground-water leading to falling water tables and depletion of economically accessible ground water in increasing number of locations.

A watershed development programme primarily addresses the sustainability issue through the efficient and sustainable use, equitable access and decentralised control of water resources. An appropriate micro-watershed development programme contributes to these objectives through decisions influencing erosion of upland soils, sedimentation of rivers, reservoirs and flood planes; and control of floods, all of which can influence the deterioration of forest, pasture and agricultural land. Through the appropriate interventions for watershed development, the issues of soil erosion, soil fertility, ground water level, remunerative cropping pattern, cropping intensity, forest-fodder-biomass production, levels and types of energy inputs and potentialities of renewable energy sources can be addressed besides integrating them for the optimal contribution towards sustainable development.

Figure 1

MAP OF HYPOTHETICAL WATERSHED



2.0 Objectives of Sustainable Development

In the context of planning for micro-watershed, the objective of sustainable development broadly would be to balance the economic development with the carrying capacity of the ecosystem. Since such a development plan cannot be a one-shot, one-time intervention and would necessarily be a continuing process over a long period of time, the broad objective of sustainability of ecosystem needs to be defined in terms of lower order but concrete objectives. The planning process is significantly aided by the measurability of the objectives. The operational plan can be evaluated with reference to these multiple objectives. From the experience of implementation of over a hundred micro watershed projects which we have examined, the local decision makers and the implementing organisations have accepted the following set of objectives as comprehensive for evaluating micro-watershed development plan. The objectives are :

(i) Minimize Soil Erosion (alternatively : Maximize Saving in Soil Erosion)
(ii) Maximize Irrigation Water availability in reservoir
(iii) Maximize ground water usage (by minimizing the loss of run-off water)
(iv) Minimize dependence on external biomass resources, i.e. fuelwood and fodder (or maximize value of local biomass - fuelwood and fodder)
(v) Maximize employment generation

From a broader viewpoint, these objectives also capture the conflicting interests of different sections of population in the area and the contradiction between the long-term versus short-term gains of development. These five objectives can be captured as three distinctive objectives with distinctive impact on the overall development. This three way categorisation of objectives is :

(i) Monetary benefits to land owners
(ii) Employment benefits to landless and other labourers
(iii) Soil conservation, which promotes long-term sustainability of land.

Benefits accruing from the increase in irrigation water and ground water availability and from value of fodder and fuelwood can be estimated in monetary value terms. These monetary benefit accrues directly to the land owning section. Fodder availability would also benefit owners of livestock. The landless and labouring classes benefit from the employment generation - both from the projects as well as increased regular activities such as afforestation and pasture land development. Value preferences of a community, expressed through community leaders, over these two objectives rests on the equity issue, i.e. the distribution of the benefits of the watershed development plan between the landed and landless sections. Control of soil erosion is treated as a separate objective since it refers to the long-term sustainability of land, which is the very basis of the existence of the local community. Thus, soil erosion is not treated in terms of its impact only on monetary value of agriculture but is considered in a larger sense of sustainable development.

The three objectives together adequately capture the basic concerns of sustainable development - specifically the monetary value objective relates to sustained economic benefits to the land owners, employment objective provides sustained economic benefit to the labouring sections and soil conservation deals with the long-term land sustainability and thereby the survival of the community. It is apparent that the three objectives would emerge in conflict in plan decisions - but within the confines of the local community dynamics, the value preferences of the representatives of the community can help balance the conflict among these objectives by choosing a watershed development plan which maximizes the value preference over these objectives. As discussed later, we have used the value function approach to model the preferences of the representative committee of local community.

3.0 Watershed Development Plan Options, Constraints and Database

Essential prerequisite for development planning is to define the existing relationships in the micro-watershed area in terms of erosion rates, reservoir sedimentation, trends in reduction of ground water level and available irrigation water and production losses in upstream and downstream. This exercise helps in estimating the impact of the proposed plan options over the status quo regime. A watershed development plan consists of a package of options, each option having a measured impact on the objectives. Each option differ in terms of decisions on the essential elements of development plan such as extent of water resource management, animal husbandary, forest and pasture management and change in cropping pattern. The development options relates mainly to land, water and biomass including livestock, agricultural and human waste. The options may also be classified in two categories - protective biological (e.g. tree and grass cover) and protective non-biological (e.g. contour bunds[1], gully[2] plugs, check dams). Watershed development planning essentially is the process of selecting a package of these options which maximizes the preferences among the multiple objectives while meeting the constraints.

3.1 Project Options

Project or programme options are essentially independent decision variables, the selection of each contributes to the plan value. For micro-watershed, the project options and decisions are as follows :

[1] Contour bunding refers to putting up of low bunds along the contour to retain soil and water.

[2] Gullies are pathways eroded by the passage of water. Neglect of a nascent gully leads to its deepening and widening over time. Gullies can be treated by vegetation or check dams either porous or non-porous.

Project Option	Decisions
1. Check dams	Size and Location of each check dam
2 Contour Bund	Total area under contour bunding
3. Gully Checks/Plugs	Size and Location of Gully checks/plugs
4. Pasture Development	Land barricaded and developed (i) naturally (ii) by seeding
5. Afforestation	Land afforested
6. Pond Development	Pond Size

For check dams, and gully checks cost and benefit data are evaluated in terms of each objective over a twenty year planning horizon for various potential locations and size combinations. Similarly, cost and benefits from other options are also evaluated in terms of each of the three objectives over the planning horizon. Project options considered for planning are a limited viable set of already pre-evaluated independent project options.

3.2 Constraints

Relevant constraints for the micro-watershed programme relates primarily to the investment budget, availability of land for afforestation, pasture development and contour bunding and desired lower limits on employment generation and soil conservation. Budget constraint limit is essentially determined by the funds allocated for investment in the watershed development programme. Decision of maximum land availability for afforestation. pasture development and contour bunding is area specific and is decided based on survey of potentially available land for each purpose. A minimum limit on employment generation and soil conservation is decided through a dialogue with the local community representatives. To ensure overall economic viability, a constraint on monetary benefit to cost ratio is also included.

3.3 Database

Effective planning requires reliable and adequate database. For the watershed development planning the database requirement include information on physical resources as well as socio-economic relationships. The information on physical resources includes data on climate, topography, geology, soils, vegetation land use, and water resources (Pereira 1989). Quantified economic data on costs and benefits are essential for evaluating the plan options (Brooks et al 1986). Data required for watershed planning also depends on the planning objectives and the planning environment. The data related to environment impacts, land management techniques, financial arrangements, etc. are also essential (Sheng 1986). The data collection generally requires primary survey of the watershed area. The field oriented surveys may include data collection through questionnaires, aerial photography and interviews. At certain locations some secondary data may also be available and can be used to save time, money and efforts. Appropriate database must be developed prior to the planning.

4.0 Model Formulation

The decision problem is to select a feasible set of project options which maximizes the decision maker's value preferences over the three objectives. Decision variables are discrete as well as continuous. The impact of each decision is assumed to be linear and additive over each criteria and constraint. This is in fact ensured by apriori considering only that set of project options which are independent in terms of resource use and benefit generation. For example, in selecting the potential locations for check dams, only those locations are independently considered which are fairly isolated. From among the locations which are close-by, the best location is determined by an analysis external to the model. It is however possible to allow a larger set of options by adding constraints which allow selection of only one location among several close-by locations. However in the present model this was found unnecessary since identification of a single potential site in a sub-area was not difficult.

The resulting model formulation is mixed-integer linear programming type with three criteria, each one represented linearly. The objective space is thus three dimensional and the preference value function defined in this space. The value function, most typically shall be a non-linear function. From the general experiences of the social decision making process, such as in the present context, the value function usually can be expected to be a concave function over the three objectives. Also, since each of the objective functions are linear functions of decision variables, the value function will in turn be a concave function of the decision variables. The feasible decision space is represented by linear constraints.

4.1 Definition of Variables and Constants

Values of all constants are defined over the planning horizon unless otherwise mentioned.

4.1.1 Variables

X_{ij} = (0,1) Variables representing selection of a check dam of size j at location i.
Y_l = (0,l) Variables representing selection of stream and gully protection at location l.
Z_b = Continuous variable representing land area (hectares) to be contour bunded.
Z_{pn} = Continuous variable representing pasture area (hectares) to be developed naturally.
Z_{ps} = Continuous variable representing pasture area (hectares) to be developed by seeding.
V_f = Continuous variable representing area (hectares) to be afforested.
W_p = Continuous variable representing size of pond (cubic meter capacity).

4.1.2 Constants

M = Variable representing the net present monetary value.
S = Variable representing total soil conserved.

E = Variable representing total employment generated.
P_I = Variable representing total investment in projects.
a_{ij} = Investment for constructing check dam of size j at location i.
b_p = Investment for constructing a pond of unit size (thousand cubic meters).
c_l = Investment for stream and gully protection at location l.
d_b = Investment for contour bunding of land per hectare.
e_{pn} = Investment for developing a hectare of pasture land naturally.
e_{ps} = Investment for developing a hectare of pasture land by seeding.
h_f = Investment per hectare of afforestation.
s_{ij}^c = Soil erosion saved by a check dam of size j at location i.
s_l^g = Soil erosion saved due to stream and gully protection at location l.
s^f = Soil erosion saved per hectare of afforestation.
I^p = Irrigation water saved per unit volume of pond.
I_{ij}^c = Irrigation water saved by a check dam of size j at location i.
I_l^g = Irrigation water saved by stream and gully protection at location l.
I^f = Irrigation water saved per hectare of afforestation.
I^b = Irrigation water saved per hectare of contour bunding.
M_I = Net present monetary surplus value of a unit of irrigation water.
g_f = Ground water contribution per hectare of afforestation.
g_p = Ground water contribution per unit volume of pond.
g_{ij}^c = Ground water contribution by a check dam of size j at location i.
g_l^g = Ground water contribution by stream and gully protection at location l.
M_G = Net present monetary surplus value of a unit of ground water.
E_{ij}^c = Direct employment generated by a check dam of size j at location i.
E_l^g = Direct employment generated by stream and gully protection at location l.
E^f = Direct employment generated per hectare of afforestation.
E^b = Direct employment generated per hectare of contour bunding.
E^{pn} = Direct employment generated per hectare of nature pasture development naturally.
E^{ps} = Direct employment generated per hectare of pasture development by seeding.
E^p = Direct employment generated per unit pond size.
M_{fw} = Net present monetary value of fuelwood per hectare of forest.
M_{fn} = Net present monetary value of fodder per hectare of naturally developed pasture.
M_{fs} = Net present monetary value of fodder per hectare of seeded pasture.
B = Investment budget to finance the watershed development projects.
r_{bc} = Minimum desirable benefit-cost ratio.
L_p = Land available for pasture development.
L_p^m = Minimum land area to be developed as pasture.
L_f = Land available for afforestation.
L_b = Land available for contour bunding.
M_p = Maximum pond size.
E_m = Minimum direct employment desired.
S_m = Minimum desired soil conservation.

4.2 Model Formulation

4.2.1 Formulation of the Objectives

Three objectives are modelled as below.

(i) Maximize Net Monetary Value (M)

This objective includes three independent sources through which monetary gains accrue - irrigation water, ground water and value of fuel and fodder through afforestation and pasture development. Monetary value is measured as net present value of annual monetary surplus revenue over the planning horizon excluding initial investment cost.

Saving in irrigation water (I_w)

$$I_w = \Sigma_i \Sigma_j I_{ij}^c X_{ij} + \Sigma_l I_l^g y_b + I^f v_f + I^b Z_b + I^p W_p$$

Saving in Ground water (G_w)

$$G_w = \Sigma_i \Sigma_j g_{ij}^c X_{ij} + \Sigma_l g_l^g y_l + g_f v_f + g_p W_p$$

Monetary value of fuel and fodder (M_{vf})

$$M_{vf} = M_{fw} V_f + M_{fa} I_{pa} + M_{fs} Z_{ps}$$

Total monetary benefit (M) due to the three sources shall be:

$$M = M_I I_w + M_G G_w + M_{vf}, \text{ i.e.}$$

$$M = \Sigma_i\Sigma_j (M_I I_{ij}^c + M_G g_{ij}^c)X_{ij} + \Sigma_l(M_I I_l^g + M_G g_l^g) Y_l$$

$$+ (M_I I^f + M_G g^f + M_{fw}) v_f + M_I I^b Z_b + (M_I I^p + M_G g_p) W_p \qquad \text{(I)}$$

$$+ M_{fa} Z_{pa} + M_{fs} Z_{ps}$$

(ii) Soil Conservation (S)

$$S = \Sigma_i\Sigma_j S_{ij}^c X_{ij} + \Sigma_l S_l^g Y_l + S_f V_f \qquad \text{(II)}$$

(iii) Employment Generation (E)

$$E = \Sigma_i \Sigma_j E_{ij}^c X_{ij} + \Sigma_l E_l^g Y_l + E^f V_f + E^b Z_b + E^{ps} Z_{ps} + E^{pa} Z_{pa} + b_p W_p \qquad \text{(III)}$$

Overall objective function is modelled as a value preference function to be maximized. A representative committees of the community is considered as a single decision maker (DM). We have termed the value preference function of the DM as **Sustainability Index (SI)** since it measures in a single index the preferences of the community over the three objectives which represent the "sustainable development" ethos in the present context.

The decision problem thus is to select a set of options which maximizes the SI while meeting the constraints. Sustainability Index is denoted as :

$$SI = V(M,S,E)$$

where V is the value preference function defined over the three objectives.

The procedure for encoding the SI is identical to the one used for encoding value functions (Keeney et al 1976). A suitable mathematical expression for SI can be developed depending on the conditions which the DM's preferences satisfy. More specifically, an additive value function results if the DM's preferences satisfy joint independence conditions (Keeney et al 1976). Through a dialogue with the DM these conditions are checked. To suit mathematical treatment, objectives are often restructured (Keeney et al 1977 and Ulvila et al 1980) to assist the DM to satisfy the desired conditions. An application of encoding the SI is illustrated later on together with an application of the model for planning a micro-watershed programme.

4.2.2 Constraints

Constraints in the model are of three types :

(i) **Financial** - one financial constraint is to limit the investment within the budget and a second constraint is to ensure that the ratio of net present value of benefits to investment cost is above a desired level.

(ii) **Upper and Lower Bounds** - these are imposed by physical limitations such as land availability for afforestation, pasture development, pond construction or desired minimum level of attainment of some objectives.

(iii) **System Constraints** - these are based on the systems logic, e.g. the fact that at a given location only one size of check dam can be constructed. Similarly there are other system constraints that can take care of restrictions such as the limit on total number of check dams to be constructed or the mutual exclusiveness of some project options.

Constraints are represented as below.

(a) Initial investment in project to be within budgeted amount(B).

$$\Sigma_i \Sigma_j a_{ij} X_{ij} + \Sigma_i C_i Y_i + b_p w_p + d_b Z_b + E_{pa} Z_{pa} + E_{ps} Z_{ps} + h_f V_f \leq B \qquad \text{(IV)}$$

The L.H.S. of above expression is equal to total investment in the project (P_I).

(b) Ratio of NPV of monetary benefit (M as per expression (I)) to investment cost (P_I) to exceed or equal the prespecified value r_{bc}.

$$M/P_I \geq r_{bc} \text{ or } M - r_{bc} P_I \geq 0 \qquad \text{(V)}$$

(c) Pasture land development should be within available pasture land (L_p) and minimum desirable limit on pasture development (L_p^m).

$$L_m^p \leq Z_{pa} + Z_{ps} \leq L_p \qquad \text{(VI)}$$

(d) Afforestation should be within available land for afforestation (L_f).

$$V_f \leq L_f \qquad \text{(VII)}$$

(e) Contour bunding should be within the area amenable for contour bunding (L_b).

$$Z_b \leq L_b \qquad \text{(VIII)}$$

(f) Pond size should not exceed maximum prescribed limit (M_p).

$$W_p \leq M_p \qquad \text{(IX)}$$

(g) Employment generation should exceed minimum desirable level (E_m). Taking E from Expression (III),

$$E \geq E_m \qquad \text{(X)}$$

(h) Soil conserved should exceed a minimum desirable level (S_m). Taking S from Expression (II),

$$S \geq S_m \qquad \text{(XI)}$$

(i) Logical constraints restricting selection of only one size of a check dam at a site.

$$\Sigma_j X_{ij} \leq 1, \forall i \qquad \text{(XII)}$$

(j) Constraint restricting selection of check dams at no more than a prespecified number (G) of locations.

$$\sum_i \sum_j X_{ij} \leq G \qquad \text{(XIII)}$$

Besides above constraints, at some locations additional constraints can be imposed based on a specific system requirements. Typically such constraints are added to exclude selection of more than one check dams from a subset of locations.

4.4 Solution Algorithm

The problem formulation is mixed-integer non-linear programming type. All constraints are linear. Non-linearity is only with the objective function. Integer variables are all zero-one type. Structural constraints restrict severely the integer combinations. Solution algorithm is devised considering these aspects of the formulation. The algorithm combines the implicit enumeration with the branch and bound procedure. The procedure is a variant of integer non-linear branch and bound procedure (Garfinkel et al 1972). At every vertex, a non-linear programming problem is solved by relaxing integer condition on non-fixed zero-one variables and allowing these variables to be continuous between 0 and 1. At a vertex, some zero-one variables are fixed- some due to branching and others using implicit enumeration conditions which checks the system constraints to fix some zero-one variables. Finite number of zero-one variables ensures finite convergence of the algorithm. Concavity of the objective function and convexity of the feasible region ensure a global maximum.

5.0 Preference Modelling and Micro-Watershed Planning : An Application

Micro-watershed projects exist at several thousand locations in India. Potential number is even bigger. We have developed a model based on the planning experience with sixteen micro-watershed projects. One of the application of the model for planning a micro-watershed development programme in Alwar district in Rajasthan state of India is presented here together with the value preference modelling for encoding the sustainability index. The project area falls under a semi-arid region. Agriculture is largely rain dependent. Rainfall being meager and erratic, there is considerable need to maximize the utilisation of water. Topography of the project area is typical of small hillocks with undulations and slopes all over the area. Thus, there is a considerable scope to use established water harvesting structures. Soil of the area is affected by rill erosion. In absence of water conservation practices, most rain water is wasted as run-off, at the same time eroding the top soil. The area thus faces acute water shortage. Ground water level has gone 100 feet below the surface. Dug wells are therefore costly to make and operate. There are thirty one tubewells/open wells installed by well-off farmers but most are dry at least six months in a year. Some farmers have been making marginal bunds around the boundry of their fields but these are inadequate to significantly influence soil erosion. To be more effective, these bunds need to be developed as the contour and slope with grass pitching. Some farmers have also done gully plugging in their fields using stones which is somewhat more effective for soil conservation. However, a systematic approach to watershed development has a considerable potential to improve the existing scenario. The watershed development planning presented here is done in this context as an integrated and community-wide effort to promote sustainable development of the area. Some relevant statistics of the project location are given in Table-1.

In a pre-planning exercise, engineers identified several potential locations for check dams. At four locations, two check dam sizes (low and medium) and at three locations three dam sizes (low, medium, high) were considered to be appropriate. For stream and gully protection eight locations were identified. Maximum pond size and land available for contour bunding, afforestation and pasture development were then determined through a survey.

Table : 1
Watershed Project : Basic Statistics
(District : Alwar, State : Rajasthan, Country : India)

Population	995	
Households	Total	159
	Agriculture	59
	Dependent on Livestock	7
	Shopkeepers etc. (Self Employed)	20
	Service	45
	Agriculture Labour	28
Land	Cultivable Area (Total)	310.3 Hectares
	Irrigated	83.5 Hectares
	Unirrigated	216.8 Hectares
Water	Water Table	Below 100 feet
	Tubewells/Open Wells	31
Climate	Semi-Arid Region, Extreme Weather Conditions	
Rainfall	300 to 700 mm (Annual) (80% Rainfall from June to September)	
Soil	Sand (Loam Type)	
Topography	Small Hillocks with Undulations and Slopes	
Major Crops	Jowar, Bajara and Guwar (Monsoon Season) Mustard and Gram (in Winter on Unirrigated Land) Wheat (in Winter on Irrigated Land)	

A planning horizon of twenty years is used for computing cost, benefits and other relevant parameters and coefficients. Investment budget available for the watershed development projects was Rs 4 million. Acceptable lower limit on benefit to cost ratio was agreed to be 1.3. Planning exercise involved modelling of value preferences to encode Sustainability Index and then solving a non-linear mixed-integer problem to select the plan that maximized the Sustainability Index.

5.1 Encoding the Sustainability Index

A group of community representatives is considered as a single decision maker (DM). The three objectives were agreed upon by the DM as relevant and complete in the present decision context. Relevant ranges within which the objective values were expected to fall are as in Table-2 below. Value function defined over the three objective functions, i.e. Sustainability Index is encoded for values of these objectives within these ranges.

Table : 2
Range of Objective Values

Objective	Maximum Value	Minimum Value
1. NPV of Monetary Value (Rs Million)	4	12
2. Soil Erosion Saved (Thousand Tons)	15	50
3. Direct Employment (Man-years)	80	200

Joint independence conditions for the three objectives were first checked. For a three objective case, joint independence of any two pairs of objective with the remaining objective is sufficient condition for the joint independence of three objectives (Keeney et al 1976). DM was asked preference questions on various alternatives[3]. When asked preference between alternatives A and B where A = (12, 30, 60) and B = (8,35,60), the DM answered A≻B[4].

When asked, if employment level (E) is changed from 60 to an another but the same level for both the above alternatives, will the preference answer change, the DM answered that the preference relation will not change for any two alternatives where the level of E is changed to an another level keeping first two objective values as same in original alternatives being compared. This statement is equivalent to the statement that the pair of objectives M and S are

[3] Note : Alternatives are represented with a three dimensional vector, (M,S,E), where monetary value (M) is in Rs Million, Soil conserved (S) is in thousand tonnes and Employment (E) is in Man-Years.

[4] A ≻ B means A is preferred to B.
A ~ B means A is indifferent to B.

jointly independent of E. Similarly through a series of questions it was found that the pair M and E is jointly independent of S. For validation, it was ensured through a few questions that the pair of objectives S and E are jointly independent of M. These are sufficient conditions for joint independence of the three objectives ensuring that the value preference function representing the SI is additive.

$$V(M,S,E) = SI = \lambda_M V_M(M) + \lambda_S V_S(S) + \lambda_E V_E(E) \qquad \text{-(A)}$$

where $V_M(M)$, $V_S(S)$ and $V_E(E)$ are independent value functions defined over objectives M, S and E respectively. Each value function is scaled with value 0 to 1 over the minimum to maximum range of the objectives. Each λ is an appropriate scaling constant such that

$$\lambda_M + \lambda_S + \lambda_E = 1 \text{ and } \lambda_M, \lambda_S, \lambda_E \geq 0 \qquad \text{- (B)}$$

Value function over each objective is independently encoded and the scaling constraints are then determined by encoding joint preferences. The value function over money, i.e. $V_M(M)$, was encoded as follows :

Define : $V_M(4) = 0$ and $V_M(12) = 1$

Value function is assessed using mid-value splitting method (Keeney et al 1976). Definition of mid-value was explained and illustrated to the DM before the question answer session. Typical questions and answers summary is as follows :

Q : For M, minimum to maximum value range is from Rs 4 million to 12 million. Given a choice, can you specify a value (called mid-value) such that you would be indifferent to move from Rs 4 million to the mid-value as from the mid-value to Rs 12 million.

A : The value shall be around Rs 6.72 million. (Analyst denotes this value as $M^{0.5}$ and obviously assigns $V_M(M^{0.5}) = V_M(6.72) = 0.5$).

Q : What is your mid-values respectively between Rs 4 million and 6.72 million and Rs 6.72 million and 12 million?

A : Rs 4.96 million and Rs 8.96 million respectively.

Continuing the questions-answers as above, the values in Table-3 are obtained.
A least-square fit using non-linear regression for the functional form

$$V_M(M) = b(1-e^{\alpha(M-4)}) \qquad \text{- (C)}$$

yields :

$$V_M(M) = 1.23\,(1-e^{-0.198(M-4)}) \qquad \text{- (D)}$$

Similar procedure for encoding $V_S(S)$ and $V_E(S)$ yields :

$$V_S(S) = 1.08\,(1-e^{-0.066(S-15)}) \qquad \text{- (E)}$$

$$V_E(E) = 1.20\,(1-e^{0.0146(E-80)}) \qquad \text{- (F)}$$

Table : 3 DM's Values Over Monetary Value Objective	
M (Rs Million)	$V_M(M)$
4.00	0.000
4.40	0.125
4.96	0.250
5.76	0.375
6.72	0.500
7.68	0.625
8.96	0.750
10.40	0.875
12.00	1.000

Figures 2, 3 and 4 show plots for V_M (M), V_S (S) and V_E (E) respectively.

Two more questions are asked to decide scaling constants:

Q : In the following comparision what is your value for M^* ?
(12,15,80) ~ (M^*,15,200).

A : M^* = Rs 11.5 million.

Q : What is your S^* value for the following?
(4,50,80) ~ (12,S^*,80).

A : S^* = 26 (Thousand tons).

From these two answers we get :

$\lambda_M = \lambda_M V_M (11.5) + \lambda_E$ - (G)

$\lambda_S = \lambda_M + \lambda_S V_S (26)$ - (H)

From equations (D)and(E):V_M (11.5)=0.9514 and V_S (26)=0.5575

Equations (G), (H) and (B) give :

$\lambda_M = 0.302$, $\lambda_S = 0.684$ and $\lambda_E = 0.014$

$$SI = 1.126 - 0.371\, e^{-0.198(M-4)} - 0.738\, e^{-0.066(S-15)} - 0.017\, e^{-0.0146(E-80)}$$

Figure 2

Value Function over Money-Vm(M)

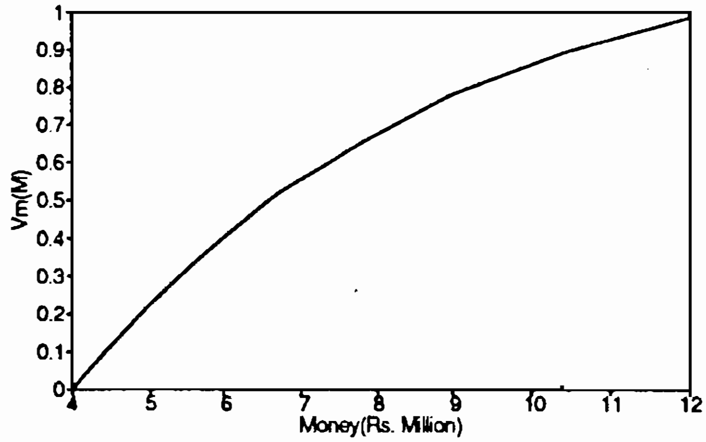
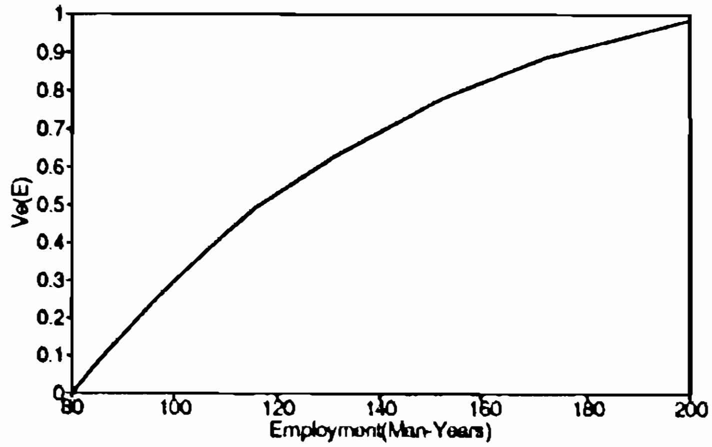


Figure 3

Value Function:Soil Erosion Saved-Vs(S)

Figure 4

Value Function over Employment-Ve(E)



5.2 Optimal Plan Selection

The optimization problem now is to select a package of projects which maximizes the SI and satisfies the constraints. The problem formulation has twentyfive integer zero-one variables, five continuous variables, eighteen linear constraints (including nine system constraints) and a non-linear objective function. The problem was solved using an algorithm based on branch and bound procedure combined with implicit enumeration as mentioned in section 4.4. The optimal plan is given in Table-4 and resulting values of the three objectives and the SI are given in Table-5. For comparision these tables also include the corresponding information for a plan selected for implementation by local authorities (Previous Plan). Both plans have same investment budget of Rs 4 million.

Table : 4
Selected Plan Options and Investment (Rs Thousand)

No.	Options	Previous Plan Investment	Optimal Plan Investment
1	Earthen Dam	2080	2080
2	Check Dam	708*	684+
3	Check Dam	725*	334++
4	Pond Development	157	244
5	Afforestation	82	162
6	Pasture Development	98**	180+++
7	Contour Bunding	80	144
8	Stream/Gully Protection	70	188
	Total	4000	4000

* Large dams at location 1 and 3. + Large dam at location 2.
++ Medium dam at location 3. ** Pasture development naturally.
+++ Pasture development by seeding.

5.3 Analysis of Results

Results in Table-4 show that for Optimal Plan monetary value and employment objectives are nearly twentyfive percent higher and soil conservation is forty percent higher compared to the Previous Plan. The Previous Plan was developed by a non-government organisation working in the area. This plan was under active consideration for implementation. Optimal Plan recommends greater investment in development options related to afforestation, pasture development, pond development; contour bunding and stream/gully protection besides recommending one large and one medium size check dam over two large check dams in the Previous Plan. This result is quite typical for development projects where the funding agencies and local government authorities tend to emphasise investment in construction projects which can be physically planned with targeted delivery and have apparent benefits rather than emphasising overall local area development options such as afforestation. pasture development, etc. which yield slow results. From the view-point of local community and its sustainable development, the Optimal Plan is obviously far superior.

Table : 5
Objective Function Values

Objective	Previous Plan	Optimal Plan	% Gain
Monetary Value (Rs Mil.)	6.32	7.81	23.6
Soil Conserved (Thou.Tons)	22.12	30.96	40.0
Employment (Man-years)	92.6	116.2	25.5
Sustainability Index	0.45	0.71	--
Benefit-Cost Ratio	1.58	1.95	23.4

5.4 Sensitivity and Policy Analysis

At optimality we find that the budget amount (Rs 4 million) is fully used. The benefit-cost ratio for Optimal Plan is more than the pre-specified limit. This suggests that an increase in budget funds can further improve the SI while meeting the benefit-cost ratio constraint. Additional budget can be used for pond development, additional check dams and contour work which is still possible. Land constraint for pasture and afforestation are binding at optimality. Four more runs were therefore taken each with different budget levels. Table-6 gives the objective function values with different budget levels, keeping all other parameters same.

Figure 5 shows the relationship of Sustainability Index with budget level. From Table-6, it is apparent that investment budget limitation has a major impact on the objective values and the SI. Additional investment beyond present budget of Rs 4 million has scope to yield high returns. In fact upto a budget of Rs 7 million, the marginal increase in benefit-cost ratio itself is close to 1.3, besides additional benefits of soil conservation and employment.

Figure 5

Budget vs Sustainability Index

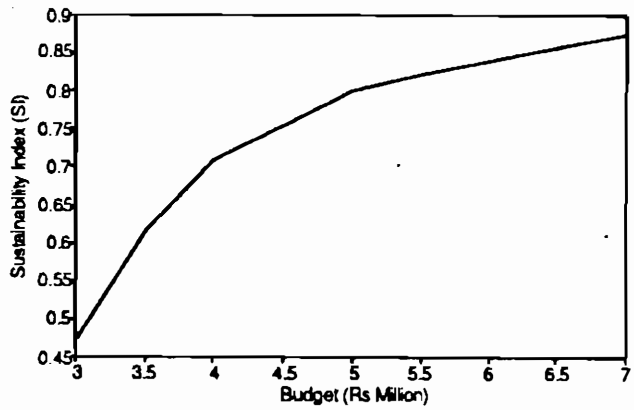


Table : 6 Objective Function Values With Different Budget Levels					
Objectives	Budget Levels (Rs)				
	3 mil.	4 mil.	5 mil.	6 mil.	7 mil.
Mon.Value (Rs.Mil)	6.15	7.81	9.28	10.61	11.89
Soil Cons (000 Tons)	23.11	30.96	34.49	35.56	37.08
Employment(Man-yrs)	80.0	116.2	125.6	132.2	136.8
Sustainability Index	0.47	0.71	0.80	0.84	0.88
Benefit-Cost Ratio	2.05	1.95	1.86	1.77	1.70

6.0 Summary and Conclusions

Micro-watershed planning primarily addresses the issue of integrating varied development programmes through the efficient use, equitable access and decentralised control of water resources. In this paper, a planning model is developed which considers three independent objectives - economic benefits, soil conservation and employment generation. The three objectives are found to be not only adequate for evaluating decisions but also as representative to serve varied interests of the community. The monetary benefits accrue essentially to land and cattle owners; employment benefits the landless and soil conservation contributes to the long-term sustainability of land - the very basis for the existence of the community.

The project options available to a planner are check dams, gully checks, contour bunds, pond development, pasture development and afforestation. Check dams and gully checks are constructed at some prespecified locations in varying sizes. These are discrete options and are represented by zero-one variables. Investment budget is one of the major constraints, besides the availability of land for pasture development and afforestation. These apart there are systems constraints such as for example to restrict the selection of more than one check dam at a location. To ensure economic returns a constraint with lower bound on benefit-cost ratio is also included. The decision maker can also specify lower limit constraints on the achievement of one or more objectives. The model formulation results in a multiple objective mixed-integer linear formulation wherein all objectives and constraints are linear functions of decision variables.

A real-life application of the model is presented. Planning horizon is taken as twenty years. A representative group of community is considered as a decision maker. Value function approach is used to model the preferences of the decision maker. Through a series of question and answers on decision maker's preferences it is found that the preferences over the objectives fulfill the joint independence conditions. This means that the value function is additive. Value function is then encoded through a series of questions and answers on decision maker's preferences. A functional fit is made to represent the value function. The value function is found to be a concave function of the three objectives and also the decision variables. We have termed the value function as Sustainability Index for obvious reasons.

The decision problem thus is to select a development plan that maximises sustainability index. For the present application, the planning problem results in a concave objective function with eighteen linear constraints, twentyfive zero-one and five continuous variables. An algorithm that uses a branch and bound procedure together with an implicit enumeration logic is developed to solve the problem. The algorithm solves a continuous non-linear problem at each node of the branch and bound tree.

The resulting optimal plan, when compared to a plan developed by a local implementing agency improves substantially the achievement of each objective. A sensitivity analysis with varying budget limits is carried out which suggests that additional provision of investment budget is highly justified.

The experience of applying the planning model suggests that there is considerable scope for improvement through formal planning over the ad-hoc approach as used at present. The multiple objective framework with value function approach helps to capture the braod preferences of the local community. While this may not be adequate to resolve all inherent conflicts of interests among various sections of local community, it is still useful to reflect community's overall preference trade-offs among the objectives. Our present efforts to improve the planning approach is on two aspects.

One is to expand the model framework through :

(i) inclusion of additional project options such as for flood control, vegetative and soil treatment (FAO 1985), wider product mix through multiple use management systems (Ffolliott et al 1986) such as through livestock rearing, crop pattern changes etc.

(ii) intervention of watershed development plans with energy planning through interlinkages such as biomass, micro-tydel, energy for irrigation etc.

(iii) integration of other environment aspects influencing the quality of life through drinking water availability, sanitation etc.

The other aspect deals with the development of an information system for watershed management. Quality and adequacy of data is a pre-requisite for meaningful planning. Our work on information system includes :

(i) Creation of general database for watershed management such as data on technologies, costs, crops, etc.

(ii) Creating methodology for local data collection through surveys, interviews etc. As an aid to the local planner, this database will also include local data collected at a large number of micro-watershed projects already implemented.

Planning becomes reality only through the implementation. During implementation, plans may need adjustments. This requires creation of local competence and an institutional framework to ensure that the gains of plans are not only realised in general but distributed desirably. Micro-watershed development creats long-term benefits for the community. Sustainable development however requires equitable access of these benefits to all in the community. While the planning framework proposed in this paper provides a conceptual basis for sustainable development through micro-watershed development, its success shall depend on the will and ability to implement the plans.

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